Phases of Dense Quark Matter and the Structure of Compact Objects

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Abstract. The presence of quark matter in neutron stars may affect several neutron star observables and the neutrino signal in core-collapse supernovae. These observables are sensitive to the phase of quark matter that is present in compact objects. We present the first calculation of the phase structure of dense quark matter which includes a six-fermion color-superconducting interaction and show that the effect of this term can destabilize the pairing interaction, favoring phases where fewer quarks are paired. In turn, this modification of the phase structure can modify the neutrino signal, the structure of the neutron star, and the long-term cooling. We also show that, contrary to the 20-year old paradigm of the surface structure of the "strange-quark stars", the surface of these objects may consist of nuggets of strange quark matter screened by the electron gas.

The region of the QCD phase diagram at densities above a few times 10^{14} g/cm^3 and temperatures on the order of 10 MeV, is highly uncertain. Observations of neutron stars (or strange quark stars) provide us with most of the constraints on the equation of state of matter at these densities and temperatures. One of the most dramatic features of QCD, the deconfinement phase transition, is not well constrained by observations of compact objects. We may entertain a couple possibilities:

1. All neutron stars may consist entirely of hadronic matter, i.e. the central density of the maximum mass neutron star is below the critical density for the deconfinement phase transition.
2. Some neutron stars may be sufficiently dense to contain deconfined quark matter in their interiors. Such neutron stars are often referred to as "hybrid quark stars". Their central density is above the deconfinement phase transition.
3. The "strange quark matter" hypothesis may hold. Some (if not all) neutron stars are, in fact, strange quark stars.

I report on some progress in the theoretical description of hybrid quark stars and strange quark stars and the associated observable implications.

The description of dense quark matter has been recently revolutionized by the observation that the color-superconducting gaps may be on the order of 100 MeV [1, 2]. The essential features of all models of gapped quark matter are the same. When the quark chemical potential is much larger than the strange quark mass, then all nine quarks participate in the pairing, giving the color-flavor-locked (or CFL) phase. For smaller quark chemical potentials, the strange quark mass is more important and only 4/9 color-flavor combinations are paired. This is the two-flavor superconducting (or 2SC) phase.

It is known that a Lagrangian with four-fermion interactions alone can not obey the

same symmetries as QCD because the axial U(1) symmetry is not broken by any four-fermion interaction. For this reason, a six-fermion interaction, the 't Hooft interaction, is often included

$$(a) \qquad K \det{}_f \bar\psi_i \psi_j \bar\psi_k \psi_\ell \bar\psi_m \psi_n \qquad\qquad (1)$$

where $\det_f$ indicates a determinant over flavor space and K is a coupling constant. Although there is no reason to do so, many authors have neglected a term of the form

$$(b) \qquad K_{\mathrm{DIQ}} \det{}_f \bar\psi_i \psi_j^C \bar\psi_k^C \psi_\ell \bar\psi_m \psi_n \,, \qquad\qquad (2)$$

where K_{DIQ} is another coupling constant. This term is of the same order in the fermion fields and also respects the symmetries of QCD. Ref. [3] makes the first study of this term which includes its effect on the quark masses and the gaps.

The basic conclusion is that for sufficiently large values of the coupling constant, this color-superconducting 't Hooft interaction can destabilize the color-superconducting gap. The effect is summarized in Figure 1, where the masses and gaps are given as a function of the coupling constant for a fixed density and temperature. The dramatic behavior of these quantities at $K_{\mathrm{DIQ}}/K \sim 0.4$ causes the gapped phases to become unstable.
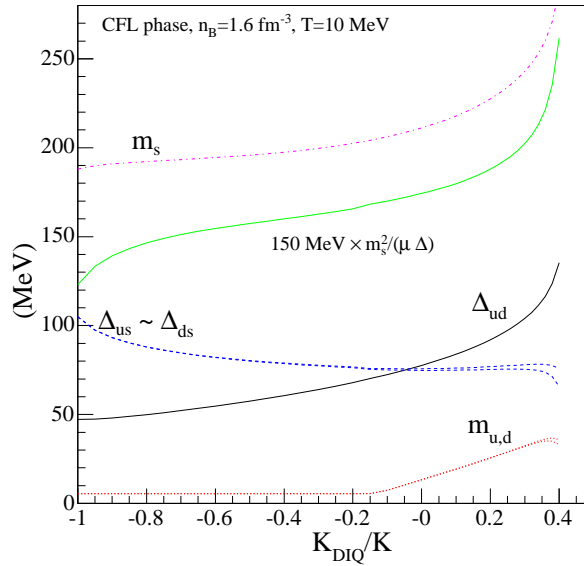

FIGURE 1. Quark masses and gaps versus K_{DIQ}/K

The presence (or lack) of a gap can affect the neutrino signal of a newly-born proto-neutron star, the cooling properties of the neutron star, and *any* observable which depends (or might depend) on the magnitude of the size of the quark gaps in hybrid quark stars or strange quark stars.

If the strange-quark matter hypothesis [4, 5] is correct, then strange quark matter may be the true ground state of matter and nuclei are a metastable state. Neutron stars may be dense enough to create a small amount of strange quark matter in the center and the entire neutron star would then be converted from normal hadronic matter to the strange

quark matter ground state as neutrons are absorbed by the strange quark matter in the interior.
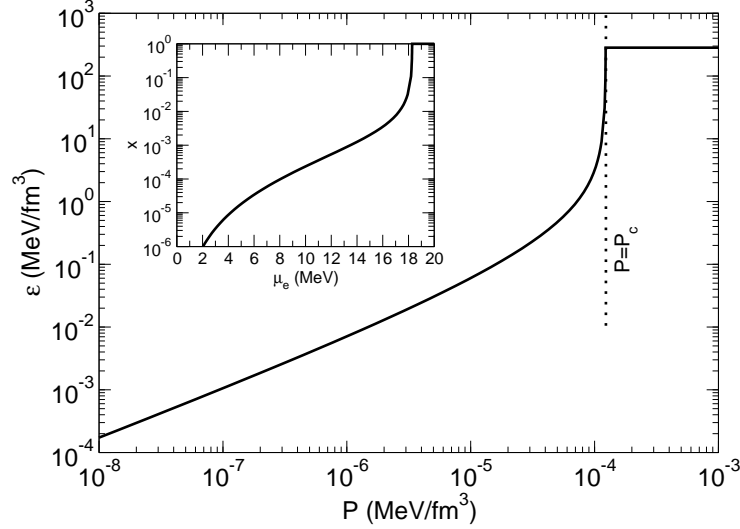
FIGURE 2. Equation of state

The long-standing paradigm for the description of strange quark stars is that, because the pressure of strange quark matter vanishes at a finite density, the surface of the strange quark star has a large density discontinuity and a large electric field [6]. However, if the surface tension between strange quark matter and the vacuum is sufficiently small, this paradigm may be incorrect [7] (also briefly mentioned in Ref. [8]). In fact, small droplets (or "nuggets") of strange quark matter may reside on the surface of a strange quark star. These droplets create a more gradual drop in density over a length of several meters above the neutron star. The corresponding gradual drop in the energy density is displayed in Figure 2. The energy density drops slowly at pressures below 10^{-4} MeV/fm^3 in contrast to the traditional picture where the energy density would discontinuously vanish at $P = P_C$. Also plotted is the volume fraction of strange quark matter in droplets as a function of the electron chemical potential in the crust. The presence of the crust decreases the electric field substantially and also decreases the photon luminosity at the surface. Neutrino scattering off quark nuggets in the crust will also modify the neutrino signal in supernovae.

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